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## Eclogitization of lower crustal granulites by fluid migration through shear zones

H. Austrheim

*Mineralogisk-Geologisk Museum, Sars gate 1, N-0562 Oslo 5 (Norway)*

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The granulite facies assemblages of the anorthositic rocks of the Bergen Arcs (stable at 800–900°C and 10 kbar) have been transformed to eclogite facies assemblages (stable at 700–750°C and 16–19 kbar) in the vicinity of Caledonian shear zones. This section of the root zone of the Caledonian mountain chain reveals a deep polymetamorphic crust where Precambrian granulites (mean density 3.02 g/cm<sup>3</sup>) and Caledonian eclogites (mean density 3.19 g/cm<sup>3</sup>) alternate on a scale of meters over a minimum area of 3 × 12 km. Detailed mapping of three localities shows that eclogites account for up to 30–45% of the rock volume. The stabilization of the eclogite mineralogy is controlled by fluids penetrating these deep crustal shear zones. The eclogitization is independent of preexisting compositional variation in this anorthosite-norite complex. The Bergen Arcs example suggests that the amount of eclogite versus granulites in the lowermost crust is a function of deformation and fluid access, rather than being controlled by *T*, *P* and rock composition alone. These relationships may explain the gradual increase in seismic velocity observed in some deep crustal sections and also the complex reflection pattern obtained from the lowermost crust in many areas.

### 1. Introduction

Information regarding the nature of the lower crust and the crust-mantle boundary is derived from three principal sources: (1) geophysical data, (2) xenolith material and (3) granulite facies terrains recognized as former deep crustal sections. In addition, theoretical and experimental petrology have had a great impact on our concepts of this part of the lithosphere. Recent research in these fields has abandoned the older model of a uniform lower crust of basaltic composition separated from the mantle by a sharp and continuous Moho. The emerging picture of the lower crust is one of great compositional diversity both vertically and laterally [1], with a predominance of mafic to intermediate granulites [2,3]. Anorthosites are encountered in xenolith populations [4] as well as in granulite facies terrains [5,6].

From investigations of exposed deep crustal sections, Fountain and Salisbury [2] find that the lower crust contains polymetamorphic and multiply deformed rocks and that the lower crust is a mixture of rocks which have evolved through deformation and metamorphism in a variety of tectonic environments.

Recent advances in geophysics have demonstrated that the Moho in many areas is not sharp but has a complex reflection pattern [7,8] with a gradual increase in seismic velocity in the lower crust [9]. O'Reilly and Griffin [10] explain this increase in seismic velocity below southeast Australia as due to an increasing amount of spinel lherzolite intercalated with gabbroic rocks. The deep crustal reflections have typically been interpreted in terms of rock boundaries, but it has also been suggested that they may represent mylonite zones [11] or layers rich in fluids [12].

The garnet granulite to eclogite phase transition has attracted attention in the discussion of the nature and evolution of the lower crust and the crust-mantle boundary [13]. Experimental results [14,15] have shown that the stable mineral assemblages in the lowermost crust in rocks of basaltic composition will be those of two pyroxene granulites, garnet granulites or eclogites and it is generally accepted today that granulites and eclogites are prominent rock types in this part of the lithosphere. The possibility that lower-grade rocks exist metastably in the lower crust has been mentioned by Kay and Kay [1] and has been argued for on kinetic grounds by Neugebauer and Spohn [16].

The present paper describes an area where arrested transformation from garnet granulites to eclogites in rocks of anorthositic-noritic composition can be observed directly and where it can be demonstrated that deformation and fluids are important parameters, in addition to pressure, temperature and rock composition.

## 2. Geological setting

The rocks dealt with in this account are from a major tectonic unit of high-grade rocks forming part of the Bergen Arcs (Fig. 1), a series of arcuate Caledonian thrust sheets centered around the town of Bergen, Western Norway [17]. This unit, which crops out over an area of more than 1000 km<sup>2</sup>, contains abundant mafic material ranging from pure anorthosite to gabbroic anorthosite and norite [18]. In addition, various members of the charnockite suite are present, the most prominent of which is the type mangerite [19].

The anorthosites of the Bergen Arcs have traditionally been correlated with the anorthosites of the Jotun Nappe to the east (Fig. 1), based on lithological and metamorphic similarities [20]. The high-grade rocks of the Jotun Nappe have been proposed by Smithson et al. [21] to represent a thick slice of lower crust emplaced in the upper crust by Caledonian deformation. However, Loeschke and Nickelsen [22] pointed out that part of the Jotun Nappe must have reached the surface in pre-Caledonian time as it is overlain by Eocambrian sediments.

The geological history of the Bergen Arcs anorthosites can be divided into two major events [23]. A protracted Precambrian (Grenvillian) orogeny which included extensive magmatic activity, deformation and granulite facies metamorphism was followed by strong but localized Caledonian reworking. The majority of the Caledonian reworking zones contain hydrous amphibolite facies mineralogy [24], but in some areas Caledonian shear zones contain an eclogite facies mineralogy.

*P*, *T* estimates for the granulite facies mineral assemblages are 800–900°C and about 10 kbar pressure while a temperature of 700–750°C and a pressure of 16–19 kbar were obtained for the eclogite facies mineralogy [23]. The position of the terrain in the *P*, *T* plane in the interval between Grenvillian and Caledonian times is not known.

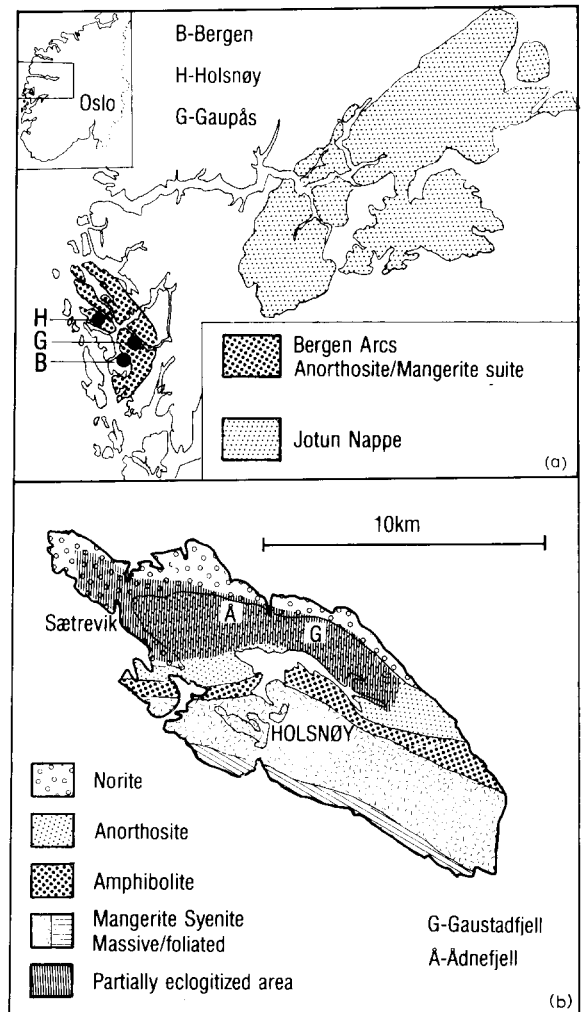


Fig. 1. (a) Location of the Bergen Arcs in relation to the Jotun Nappe. (b) Geological map of Holsnøy showing the approximate extent of the partly eclogitized area drawn on the map of Kolderup and Kolderup [18].

## 3. Field relations

Austrheim and Griffin [23] described formation of eclogites in a shear zone from Sætrevik on Holsnøy (Fig. 1), and indicated that similar shear zones are present in many parts of the Bergen Arcs.

Recent mapping in the area has revealed that eclogitization has affected a belt on northeastern Holsnøy which is 12 km long and 3–5 km broad (Fig. 1). In addition, eclogite shear zones have been found at Gaupås [25], some 40 km to the

south. The eclogites at Gaupås are found in the same belt of anorthosites as those of Holsnøy, according to the map of Kolderup and Kolderup [18]. The extent of the partially eclogitized area around Gaupås is at present not known. It is clear, however, that the eclogitization is not confined to a few localities, but occurs on a regional scale. The possibility can not be ruled out that the larger area of anorthosites which shows reworking zones with an amphibolite facies mineralogy may have developed by hydration of a former eclogite mineralogy. In this case the partially eclogitized area would be 1–2 orders of magnitude greater than observed today.

### 3.1. Description of the eclogitized area

Outside the zones of Caledonian reworking the anorthosite complex alternates between well-banded parts, where the banding is defined by cm-thick mafic layers rich in diopside and garnet, and plagioclase-rich layers. This banding is referred to as the granulite facies foliation. In the coronitic parts the granulite facies foliation is defined by parallel-orientated disc-shaped coronas. These coronas, which typically have a core of orthopyroxene surrounded by clinopyroxene and garnet, were interpreted by Griffin [26] as formed during cooling of the anorthosite complex from

magmatic temperature through a reaction between olivine and plagioclase. Griffin et al. [27] demonstrated that the corona forming reaction in this complex took place at temperatures  $> 900^{\circ}\text{C}$ .

The eclogitization is typically confined to 0.2–5 m thick shear zones. In the majority of the shear zones the granulite facies foliation is dragged into the shear zone where it becomes parallel to the new eclogite facies foliation and eventually disappears in the central part of the shear zone (Fig. 2). Some shear zones have discontinuous margins (Figs. 3 and 4) where the granulite facies foliation is abruptly truncated. Within these shear zones, remnants of the granulite facies banding are seen in rotated blocks of competent mafic layers. The new foliation defined by the eclogite minerals flows around the mafic blocks in a complex flow pattern (Figs. 3 and 4).

The eclogitization can also be seen related to macroscopic kink bands in the anorthosite (Fig. 5). Here the granulite facies foliation can be traced right through the eclogitized area with a small offset of the bands along a mm-thick vein in the center of the kink band. The transition from granulite facies mineralogy to eclogite mineralogy, as represented by change in colour from white to dark green, takes place over a distance of less than 1 cm (Fig. 5). It is important to note that the



Fig. 2. Granulite facies anorthositic rock (upper part of photo) is transformed into eclogite (dark lower part). Note the bending of the granulite facies foliation and the development of the new eclogite facies foliation (lower part).

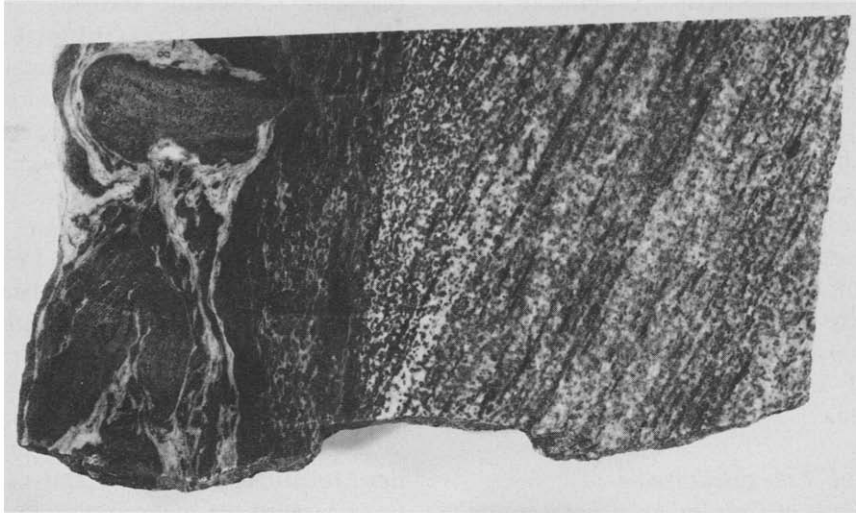


Fig. 3. Discontinuous shear zone (left-hand side) cuts granulite facies foliation in anorthosite gabbro. Note rotated block with relict granulite facies foliation (upper left corner). The light material in the eclogitized part consists of kyanite, phengite, clinozoisite, quartz and minor plagioclase. Note also the complex flow structures in the eclogitized part. Long dimension of sample is 30 cm.

margin of the eclogitizing front extends 5–10 cm outside the area actually kinked (Fig. 5). In this case the eclogitization bears a strong resemblance to hydrothermal veins [28].

In places, the eclogitization takes place in the neighbourhood of cracks (Fig. 6). Patches of eclo-

gite which apparently bear no relation to shear zones can then be seen (Fig. 6). However, the distance to the nearest shear zone is always small, generally not more than 1 m, and unsheared eclogites often can be followed to a shear zone.

So far no structural analysis of the shear zones

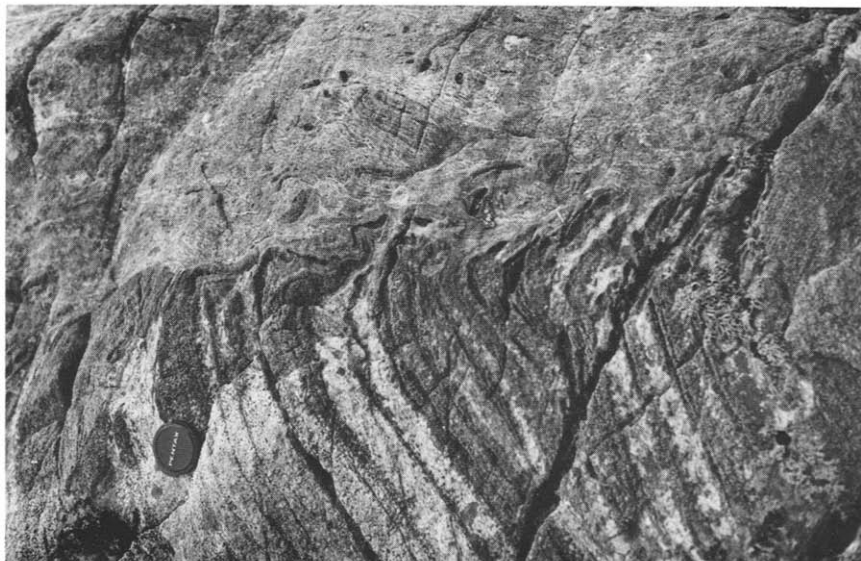


Fig. 4. Discontinuous shear zone (upper part of photo) cuts the banded anorthosite gabbro. Note blocks with relict granulite facies banding, surrounded by eclogite foliation.

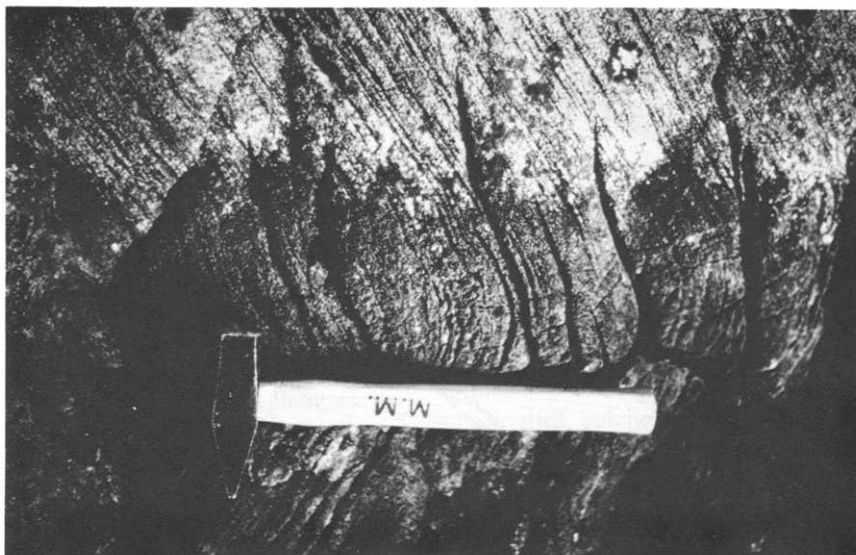


Fig. 5. Eclogitization related to kinking of granulite facies foliation. Note that the granulite facies structure can be followed into the eclogitized zone. Note also the abrupt change from granulite facies anorthositic rocks (light colour) to the eclogite facies equivalent. The eclogitizing front extends ca. 5 cm behind the kinked part.

has been undertaken. In some localities the shear zones tend to be parallel. However, in most cases they curve around lenses of granulite facies anorthosites (Fig. 7) in a complex flow pattern.

### 3.2. *Extent of eclogitization*

The amount of eclogite formed in a given

volume of rock varies from place to place. In the eclogitized belt on Holsnøy, localities of 1000 m<sup>2</sup> may be without or with only a few shear zones 1–2 m thick. In the most intensely eclogitized area, one can find localities of 1000 m<sup>2</sup> made up of completely eclogitized anorthositic material.

To quantify the extent of eclogitization, three

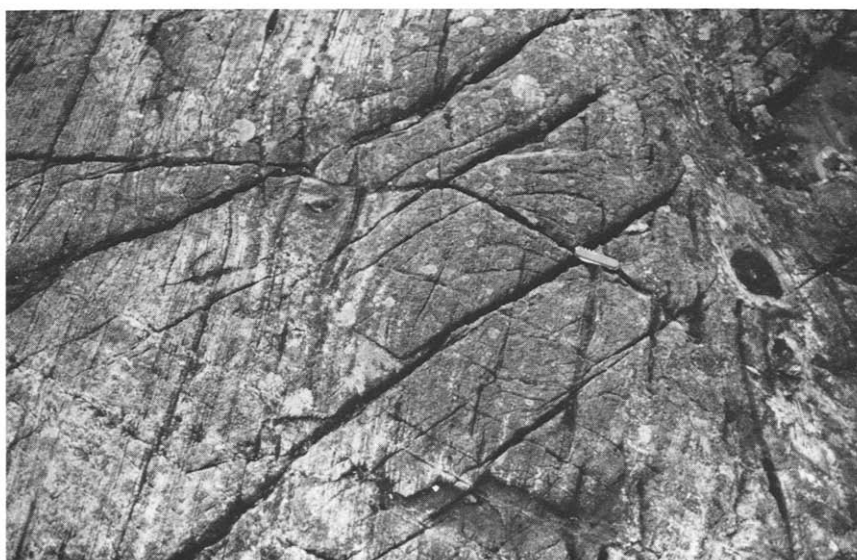


Fig. 6. Patch of eclogitized material outside a shear zone. Note the development of fracture systems/microshears.

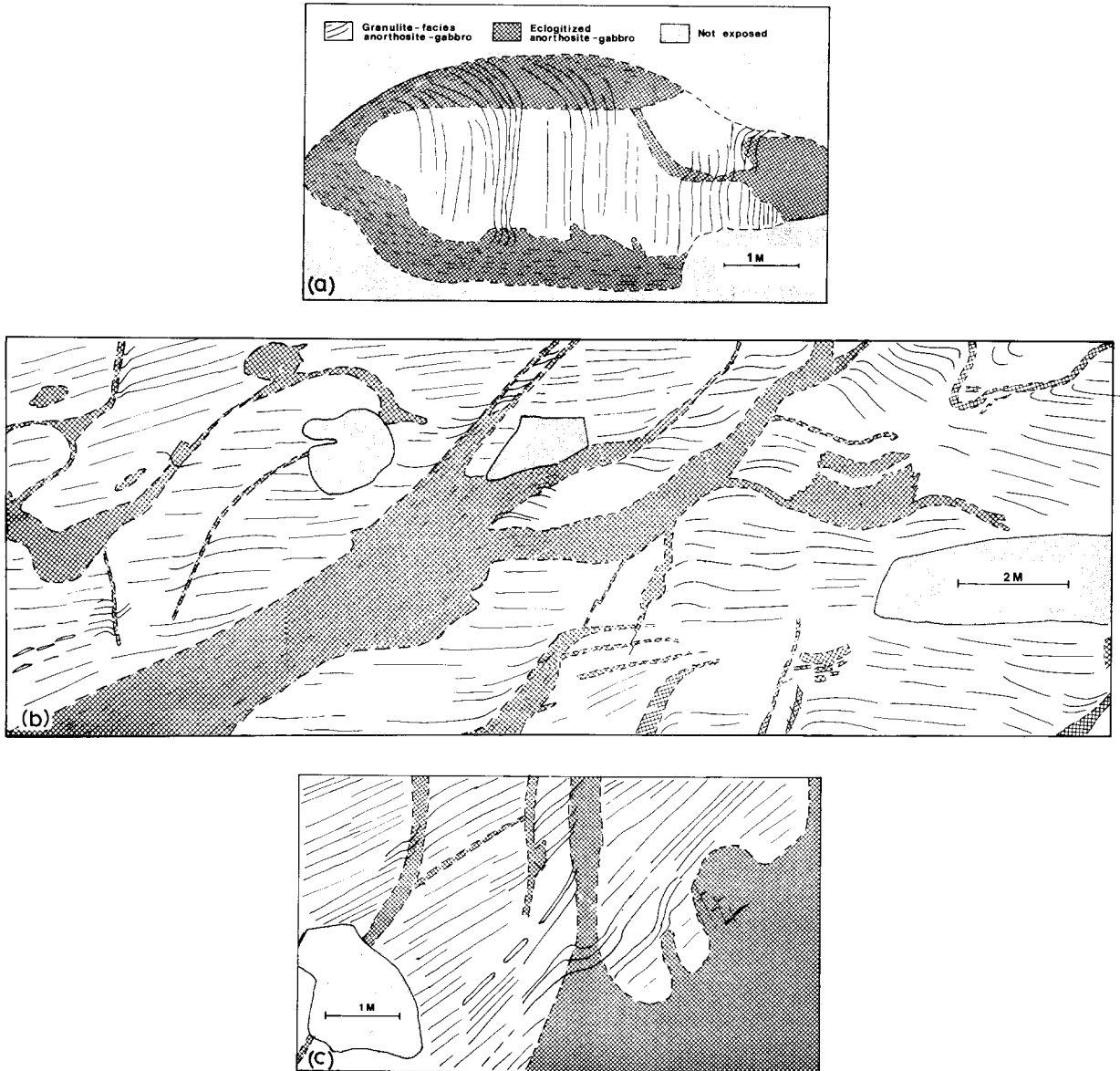


Fig. 7. Detailed maps of the three localities mentioned in the text. (a) Locality 1, southeast of Gaustadjfjell. The eclogitized part amounts to 45% of the exposed surface. Note the lens-shaped form of the preserved granulite. (b) Locality 2, the southeastern top of Gaustadjfjell. Eclogite is 30% of the exposure. (c) Locality 3, Ådnefjell. The right-hand side eclogite related to the major shear zone mentioned in the text. The eclogitized part of the mapped area amounts to 35%.

well-exposed localities of intermediate to high degree of eclogitization were chosen for detailed mapping.

*Locality 1: Southeast of Gaustadjfjell, Holsnøy.* The mapped locality is a small lense-shaped exposure of 30 m<sup>2</sup> in the hillside up to Gaustadjfjell (Fig. 1).

The exposed surface, which is surrounded by vegetation on all sides, has a strike of 010 and dips 25° to the east. The eclogitized material is confined to the border of the outcrop (Fig. 7), indicating that the eclogite extends below the cover. From Fig. 7 the eclogite part was calculated to make up 45% of this outcrop.

*Locality 2: the southeastern top of Gaustadjell, Holsnøy.* In a nearly horizontal outcrop of 3000 m<sup>2</sup> (Fig. 7) the amount of eclogite was calculated as 30%.

*Locality 3: Ådnefjell, Holsnøy.* A well-exposed horizontal area of 500 m<sup>2</sup> occurs just under the top of Ådnefjell. The area is bounded to the east by a major shear zone 5 m across, forming a small valley (Fig. 7). The amount of eclogite is approximately 35% of the mapped area.

#### 4. Mineralogical and microstructural changes related to the granulite-eclogite phase transition

The granulite-eclogite phase transition as it occurs in relation to a shear zone at Sætrevik (Fig. 1) was described in detail by Austrheim and Griffin [23]. The main change is transformation of a plagioclase-rich rock into a rock rich in omphacite where plagioclase is absent or present in minor amounts. Austrheim and Griffin [23] list the following minerals as part of the granulite (I) and eclogite (II) mineral assemblages.

I. plagioclase (An<sub>35</sub>-An<sub>65</sub>), Al-rich diopside, garnet (I) ± orthopyroxene ± sulfur-rich scapolite ± dark brown hornblende.

II: omphacite (Jd<sub>50</sub>), garnet (II), kyanite, clinozoisite, phengite, amphibole, quartz ± plagioclase.

A number of solid-solid and hydration reactions were listed to explain this transformation [23]. In the following a series of microstructural relationships, together with mineral compositions will be presented which stress the importance of the fluid phase during this transformation.

##### 4.1. Calcite in eclogite

Calcite has not been found in the granulite facies parts of the anorthosite complex. In the eclogites, calcite can be present as separate grains in equilibrium with the eclogite minerals, and more importantly as inclusions in clinopyroxenes undergoing alteration from diopside to omphacite where Ca was displaced by Na in the clinopyroxene structure [23]. The calcite inclusions indicate that this change took place in the presence of CO<sub>2</sub>-rich fluid.

##### 4.2. Microcracks

Figs. 8 and 9 are microphotographs from the same cm-thick system of microfractures penetrating the anorthositic rock at Ådnefjell (Fig. 1). Where this crack system runs through plagioclase (Fig. 8), needles of clinozoisite arranged in a

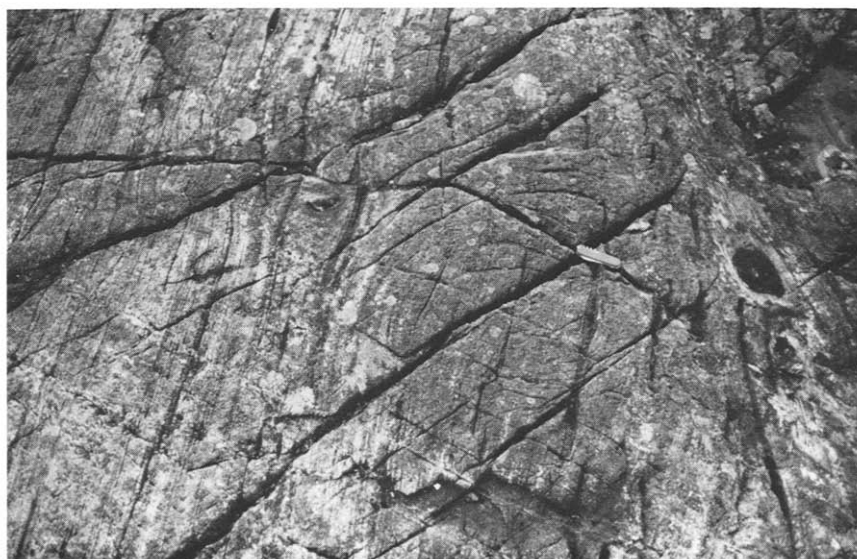


Fig. 8. Microfracture penetrating plagioclase in anorthositic rocks from Ådnefjell. Note (1) clouding of feldspar, (2) clinozoisite needles growing out from the main fracture. Plane-polarized light. Magnification 70 ×.

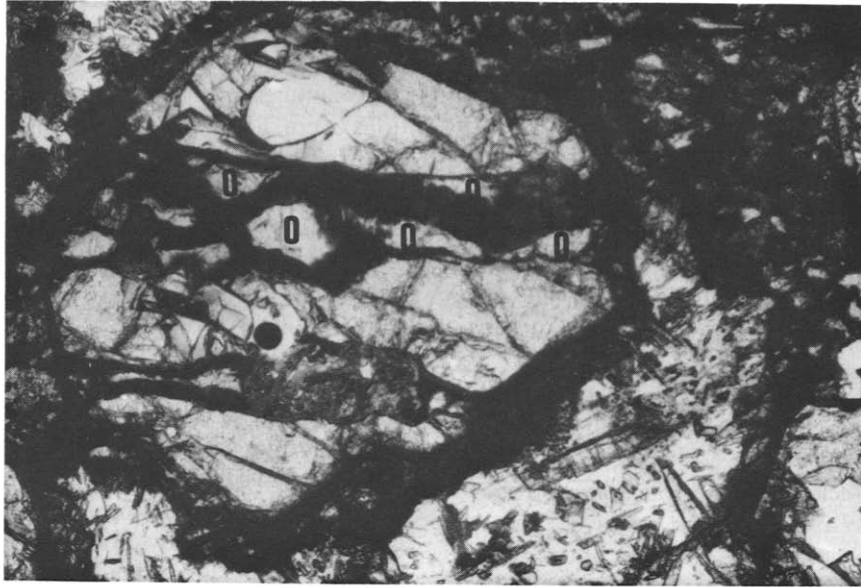


Fig. 9. Same fracture as shown in Fig. 8 penetrating garnet. Omphacite (*O*) is formed within garnet. Note clinzoisite inclusion in plagioclase. Plane-polarized light. Magnification 70 $\times$ .

rosette-like texture branches out from the crack. The crack itself is locally found to be filled with quartz, but in most cases is seen as a dark mass. The crack leads to a strong clouding of plagioclase at a distance of 1–2 cm from the main fracture.

Where the crack hits a granulite facies garnet (Fig. 9), the garnet is filled with omphacite ( $Jd_{50}$ ).

In the main eclogite bodies the granulite facies garnets are recognised as cores to the more grossular-rich eclogite facies garnets [23]. In the granu-

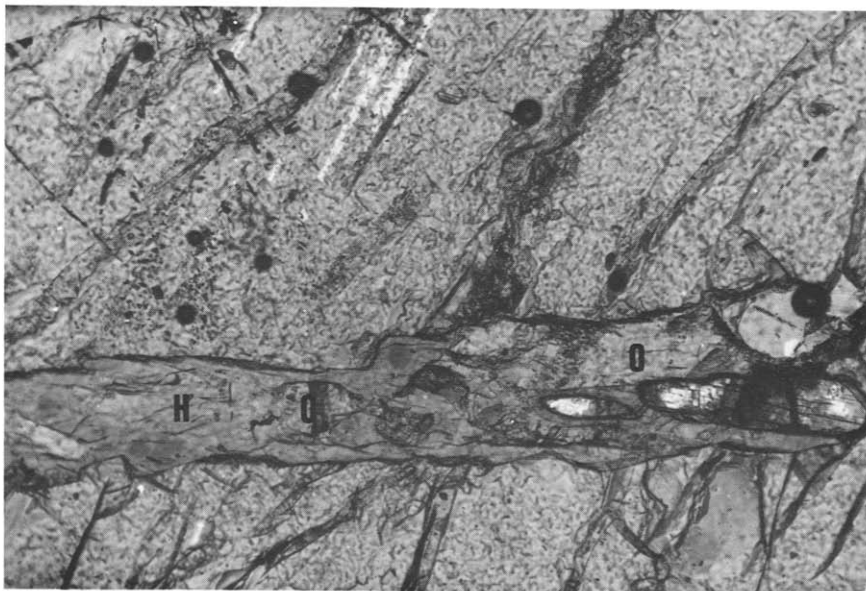


Fig. 10. Microcrack in granulite facies garnet filled with omphacite (*O*), Cl-rich hornblende (*H*), and kyanite (high relief). Plane-polarized light. Magnification 70 $\times$ .

lite facies areas these garnets are inclusion-free or locally contain inclusions of diopside. In the eclogites the old granulite garnets locally contain cracks filled with omphacite, hornblende with up to 1 wt.% of Cl, and kyanite (Fig. 10).

These relationships suggest that the eclogitization was controlled by fluids penetrating the shear zones and that there was substantial element mobility in the neighbourhood of shear zones.

#### 4.3. Density changes

Samples of granulites (13) and eclogites (21) weighing between 0.5 and 2.0 kg were collected and specific gravity was measured. The majority of the samples comes from the Ådnefjell locality and for each granulite a corresponding eclogite was collected from less than a meter away. Six additional samples of eclogitized anorthositic material, together with two mafic eclogites were also collected. The results are shown in Fig. 11. The density of the granulite facies anorthositic rocks ranges from 2.79 to 3.21 g/cm<sup>3</sup> with an average of 3.02 g/cm<sup>3</sup> and of the eclogitized anorthositic rocks from 3.06 to 3.33 g/cm<sup>3</sup> with an average of 3.19 g/cm<sup>3</sup>. The spread within each group is mainly due to variation in the bulk composition. The dependence on bulk composition is also demonstrated by the mafic eclogites which have a density between 3.5 and 3.6 g/cm<sup>3</sup>.

The eclogites of the Bergen Arcs show varying amounts of diopside/albite symplectite surrounding omphacite. Symplectite formation is related to decomposition of omphacite during uplift [29]. The density difference between eclogites and

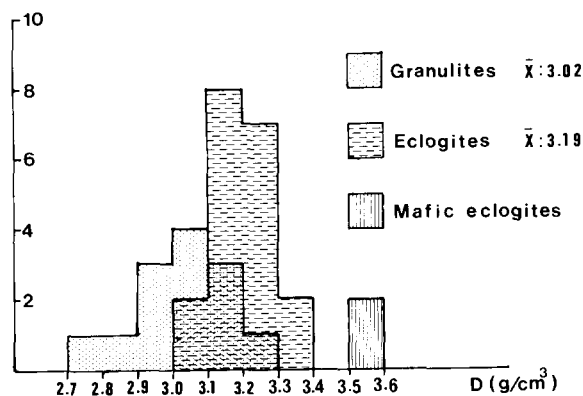


Fig. 11. Histogram showing density of granulite and eclogite facies anorthositic rocks. Two samples of mafic eclogites are also presented.

granulites as obtained by these measurements should therefore be regarded as a minimum value.

## 5. Discussion and conclusions

The Grenvillian garnet-granulites of the Bergen Arcs, with abundant anorthositic material, are a plausible lower crustal suite both compositionally and mineralogically. The Caledonian eclogites, however, were formed at depths in the crust only attained below young mountain chains, e.g. the Alps and the Himalayas. The situation corresponds to the Fountain and Salisbury [2] model where the lower crust is composed of rocks which are polymetamorphic and multiply deformed due to orogenic recycling. However, the alternation of anorthositic rocks on a meter scale between granulite and eclogite over an area of tens of km<sup>2</sup> introduces new concepts. The unique nature of the Bergen Arc exposures is more probably explained by somewhat unique tectonic processes of uplift and preservation than by rarity of the eclogite-forming process in mountain roots.

#### 5.1. Kinetic and metasomatic aspects of the granulite eclogite transition

Green and Ringwood [30] showed experimentally that the  $P$  and  $T$  where eclogites form from granulites are strongly dependent on bulk rock composition. For example, the plagioclase-out boundary at 1100° lies 10–15 kbar higher for a gabbroic anorthosite than for an alkali-poor olivine tholeiite. This indicates that the boundary between granulites and eclogites should be lithologically dependent.

The present account, on the other hand, describes a transition from granulite to eclogite which would seem to be independent of whole rock composition within the range anorthosite–gabbroic anorthosite–norite. This follows from the observation that shear zones with eclogites cross-cut the compositional layering defined by the granulite facies foliation. The regional extent of the eclogitization further demonstrates that we are not dealing with a simple  $P, T$ -isograd relation. Since the granulites and the eclogites of the Bergen Arcs must have followed the same  $P, T$  path we are left with the two following explanations:

(1) Fluids and deformation played an important role in the triggering metamorphic reac-

tion. This would require an extensive metastability in the lower crust.

(2) Small changes in fluid composition can lead to significant changes in mineral assemblages and mineral compositions [34]. Fluids can also facilitate element mobility and mass transport thereby changing the composition of a system.

The formation of eclogites with various hydrous minerals together with calcite and Cl-bearing hornblende from dry granulites strongly suggests that the fluid components were important in stabilizing the eclogite assemblages. The hornblende- and omphacite-filled veins in garnet further suggest element mobility at least on a local scale. It is therefore argued that the fluids penetrating these deep-crustal shear zones not only triggered metamorphic reactions but, more importantly, changed the thermodynamic properties and composition of the system to allow the metamorphic reactions to occur.

Fluid infiltration of the lower crust in the neighbourhood of shear zones has been reported from Southern India [31] where CO<sub>2</sub>-rich fluids cause granulite facies metamorphism and also have a subtle metasomatic effect [32]. Schuiling and Kreulen [33] relate thermal domes to a CO<sub>2</sub>-rich fluid stream from the mantle. Although the origin of the fluid penetrating the eclogite shear zones of the Bergen region is unknown, the described relationship suggests that the crust and the mantle undergo chemical exchanges via fluid motions. Regardless of this uncertainty, the described example from the Bergen Arcs shows that eclogitization of granulites can take place on a regional scale, unrelated to rock boundaries, and can produce a meter-scale alternation between granulites and eclogites.

### 5.2. *The granulite-eclogite transition and the seismic signature of the lowermost crust*

The transformation of granulites to eclogites is shown to have increased the rock density. This density change is likely to be reflected in a higher seismic velocity of eclogites as compared to granulites of the same composition and will give the partly eclogitized areas a seismic velocity intermediate between the eclogite and granulite facies anorthositic material. One can foresee from the Bergen Arcs example that the amount of eclogite versus granulite in the lower crust will vary

not only with depth and temperature, but as a consequence of deformation and fluid migration. This must mean that the increasing seismic velocity with depth observed in some lower crustal sections can take place within the same rock type and reflect a higher proportion of eclogites versus granulite due to deformation and fluid transportation in the border region between crust and mantle.

The described relationships also give support to the Matthews and Cheadle [12] and Smithson et al.'s [11] suggestions that some of the complex deep crustal reflections may be related to fluids and mylonite zones in the lower crust. Phase transitions, new foliations, and the presence of fluids may enhance the seismic reflectivity. It is thus suggested that areas with high concentration of shear zones and eclogites, alternating with low strain areas of granulites, would result in a complex reflection pattern from a lower crust like the Bergen area. Combined with the observation that deformation in low crustal terrains tends to be concentrated in parallel shear belts, this may provide an adequate explanation for the fine scale layering observed in seismic profiling from the lower crust [35,36].

The quantification of these ideas in relation to the Bergen Arcs must await a detailed mapping and structural analysis of the eclogite shear zones combined with laboratory measurements of seismic velocities of the actual rocks and the shooting of seismic profiles in this area.

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